Introduction to the Ionosphere: Part 1

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Based on the 2011 presentation delivered by Anita Aikio

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Outline

- Neutral Atmosphere
  - Regions by temperature
  - Regions by composition
- Ionosphere
  - Regions
  - Composition
  - Temperatures
  - Dynamics
  - Ionization sources
  - Latitudinal variations
  - Characteristics of D, E, and F regions

- Neutral atmosphere

Atmospheric regions by temperature

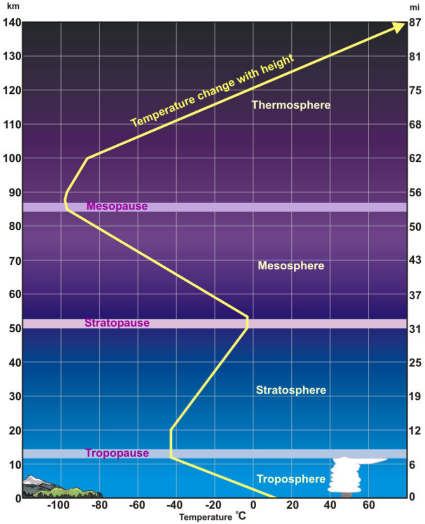


Figure: Atmospheric temperature profile.

- Troposphere is heated by the warm ground and the infrared radiation is emitted out radially => T decreases with height.
- Tropopause at 12–15 km, T_{min} $\sim$ -53° C.
- In the stratosphere, ozone (O_3) layer at 15 – 40 km absorbs solar radiation. Stratopause at 50 km with T_{max} $\sim$ 7° C.
- In the mesosphere heat is removed by radiation in infrared and visible airglow as well as by eddy transport. Mesopause close to 85 km with T_{min} $\sim$ -100° C.
- In thermosphere UV radiation is absorbed and it produces dissociation of molecules and ionization of atoms and molecules.

Thermospheric temperature

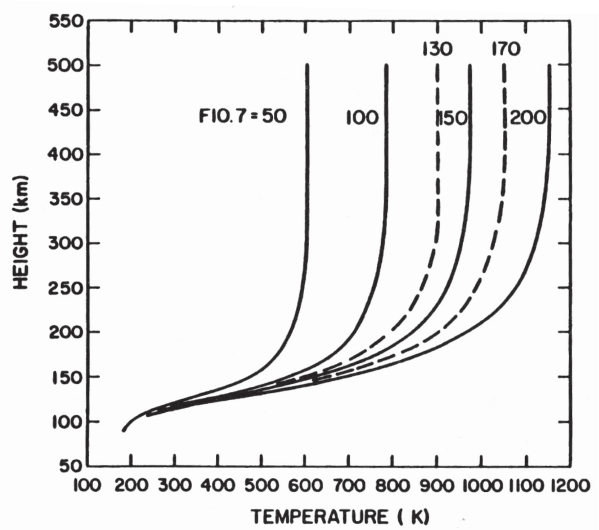


Figure: The variability in the thermospheric temperature for different values of the solar radio flux index $F_{10.7}$ in units of 10^{-22} $\mathrm{Wm^{-2}Hz^{-1}}$ at 1 AU.

Atmospheric gas in a stationary state

Above to the surface of the Earth, the atmospheric pressure p and density n are given

$$p = p_0 \exp\left[-\int_{z_0}^{z} \frac{mg}{k_B T(z)} dz\right] = p_0 \exp\left[-\int_{z_0}^{z} \frac{dz}{H(z)}\right] \quad (1)$$

and

$$n = n_0 \frac{T_0}{T(z)} \exp\left[-\int_{z_0}^{z} \frac{dz}{H(z)}\right] \quad (2)$$

where p_0 and n_0 are values at a reference height z_0.
if the atmosphere is isothermal (T=constant), the scale height H

$$H = \frac{k_B T}{mg} \quad (3)$$

is independent of altitude and then the the hydrostatic equations are

$$p = p_0 \exp\left(-\frac{z - z_0}{H}\right), \; n = n_0 \exp\left(-\frac{z - z_0}{H}\right). \quad (4)$$

Atmospheric regions by composition

1. The homosphere is the region below about 100 km altitude, where all gas constituents are fully mixed; i.e. the relative concentrations of different molecular species are independent of height. This is caused by turbulent mixing of the air.
2. The turbopause is the upper boundary of the homosphere at an altitude of about 100 km.
3. The heterosphere is the region above the homosphere. In the absence of atmospheric turbulence, each molecular species distribute with height independently of the other species (according to its own scale height)=> At great altitudes light molecular species dominate.

Composition in the heterosphere

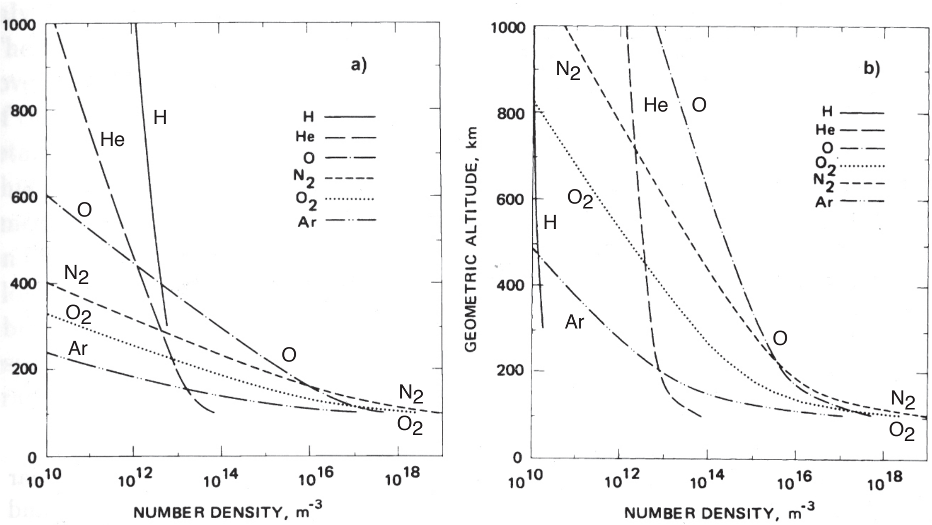


Figure: Atmospheric composition during (a) solar minimum and (b) solar maximum (U.S. Standard atmosphere, 1976).

- Ionosphere

  In the solar wind plasma, and in many parts of the magnetosphere the ionization degree is 100%.

  What is the maximum ionization degree in the ionosphere?

- Ionosphere

  At maximum 1‰ of the neutral atmosphere is ionized.

Ionospheric regions

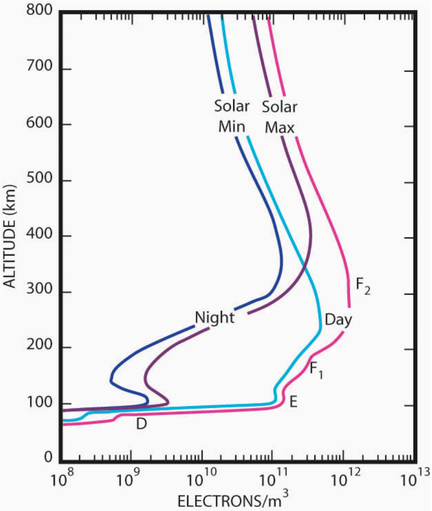


Figure: Typical ionospheric electron density profiles.

Ionospheric regions and typical daytime electron densities:

- D region: 60–90 km, $n_e = 10^8$–10^{10} m^{-3}
- E region: 90–150 km, $n_e = 10^{10}$–10^{11} m^{-3}
- F region: 150–1000 km, $n_e = 10^{11}$–10^{12} m^{-3} .

Ionosphere has great variability:

- Solar cycle variations (in specific upper F region)
- Day-night variation in lower F, E and D regions
- Space weather effects based on short-term solar variability (lower F, E and D regions)

Ion composition

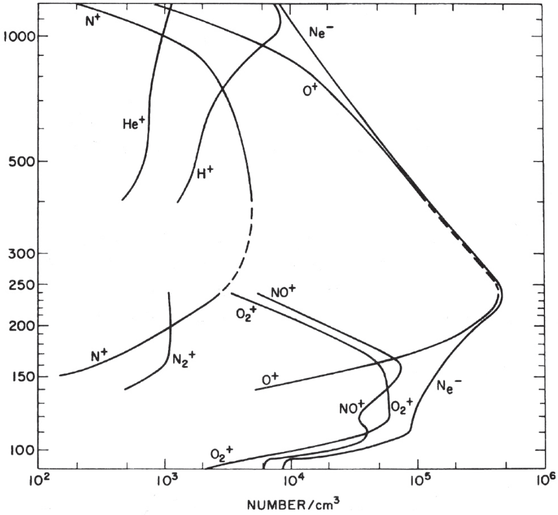


Figure: Daytime solar minimum ion profiles.

- O^+ dominates around F region peak and H^+ starts to increase rapidly above 300 km.
- NO^+ and O_2^+ are the dominant ions in E and upper D regions (Ion chemistry: e.g. $N_2^+ + O \longrightarrow NO^+ + N$).
- D-region (not shown) contains positive and negative ions (e.g. O_2^-) and ion clusters (e.g. $H^+(H_2O)_n$, $(NO)^+(H_2O)_n$).

Ionospheric temperatures

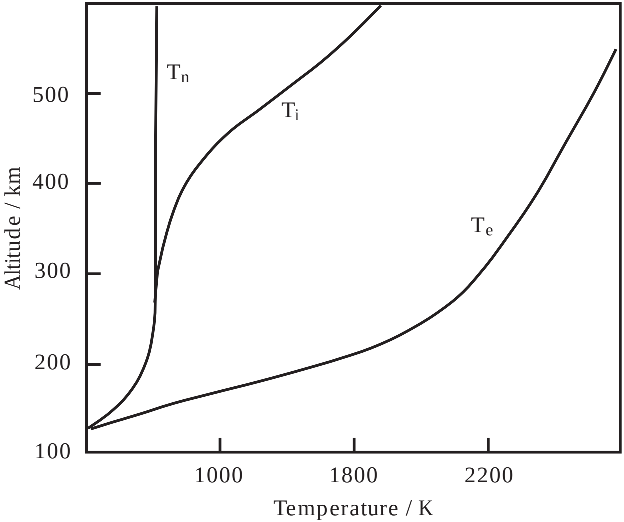


Figure: An example of neutral, ion and electron temperature profiles.

Dynamics of the ionosphere

The important equations for ions (number density n_i) and electrons (number density n_e) in the ionosphere are the continuity equations:

$$\frac{\partial n_{i,e}}{\partial t} + \nabla \cdot (n_{i,e}\mathbf{v}_{i,e}) = q_{i,e} - l_{i,e}, \tag{5}$$

where q is the production rate per unit volume and l the loss rate per unit volume; and the momentum equations:

$$n_i m_i \left(\frac{\partial}{\partial t} + \mathbf{v}_i \cdot \nabla\right) \mathbf{v}_i = n_i m_i \mathbf{g} + e n_i (\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) - \nabla p_i - n_i m_i \nu_i (\mathbf{v}_i - \mathbf{u}) \tag{6}$$

$$n_e m_e \left(\frac{\partial}{\partial t} + \mathbf{v}_e \cdot \nabla\right) \mathbf{v}_e = n_e m_e \mathbf{g} - e n_e (\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \nabla p_e - n_e m_e \nu_e (\mathbf{v}_e - \mathbf{u}) \tag{7}$$

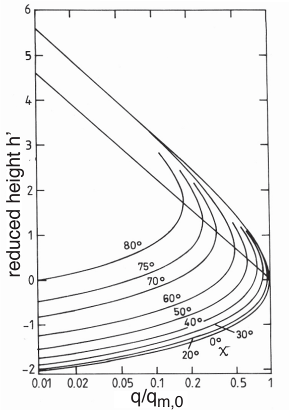
where $\mathbf{E}$ is electric field, $\mathbf{B}$ is magnetic induction, p_i and p_e are the pressures of the ion and electron gas, and the ion-neutral and electron-neutral collision frequencies are denoted by ν_i and ν_e, respectively.

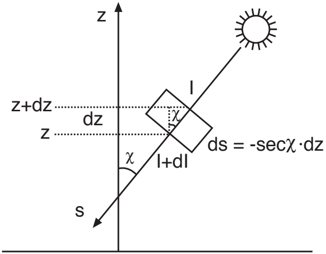
Ionization source: solar radiation

Chapman production function by using a height variable $h' = h - \ln \sec \chi$:

$$q(\chi, h') = q_{m,0} \cos \chi \cdot \exp \left[1 - h' - e^{-h'} \right] ,$$

where χ is the solar zenith angle and $h = (z - z_{m,0})/H$, where H is the atmospheric scale height.





- With larger zenith angle χ, the peak of ionization rate rises in altitude and decreases by a factor $\cos \chi$.

Ionization source: particle precipitation (electrons)

- High-energy electrons deposit the energy at lower altitudes.

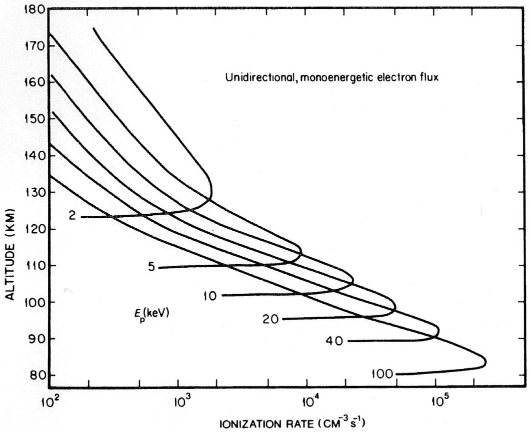


Figure: Ionization rate for monoenergetic electrons with energies 2–100 keV.

Ionization source: particle precipitation (protons)

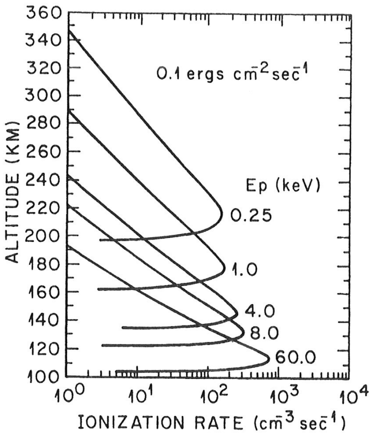


Figure: Ionization rate for monoenergetic protons with energies 0.25–60 keV (Rees, 1982).

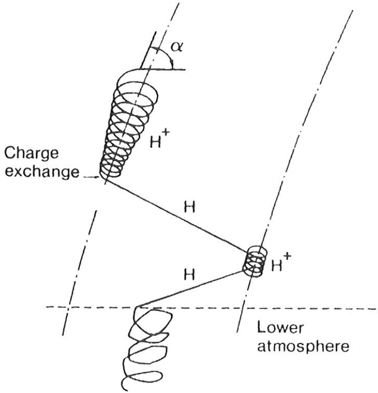


Figure: Protons may make charge exchange with neutral hydrogen.

Ionosphere at high, middle and low latitudes

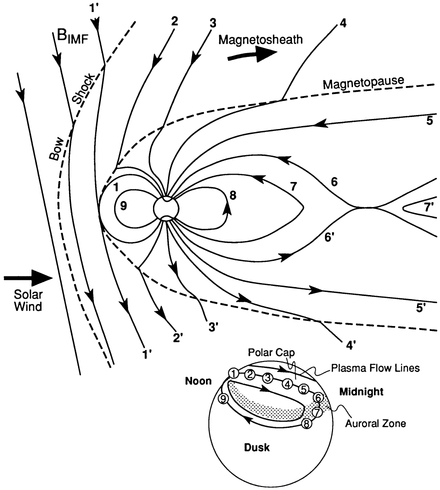


Figure: IMF coupling to the magnetosphere.

- High-latitude ionosphere (polar cap, cusp, auroral oval): intense electric fields mapping from the magnetosphere, particle precipitation, effects of magnetospheric substorms.
- Mid-latitude ionosphere: occasionaly high-latitude electric fields may penetrate to mid-latitudes, effects of magnetic storms.
- Low-latitude ionosphere: small electric fields, high day-time conductivities due to solar radiation (equatorial electrojet).

High latitudes: Auroral oval and the polar cap

- The instantaneous distribution of auroral activity versus magnetic local time (MLT) and magnetic latitude (MLAT) was found by Feldstein and Starkov in 1967 to be given by an oval-shaped belt called the auroral oval.

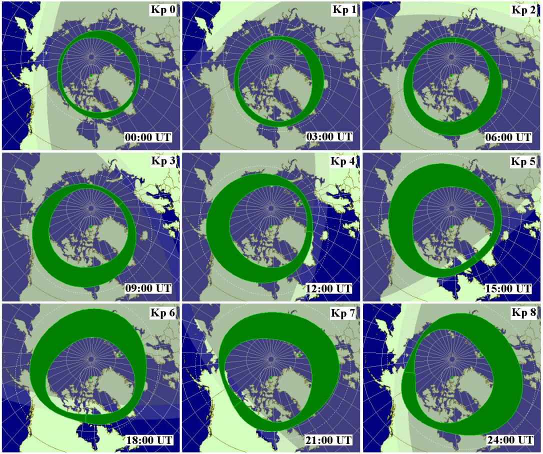


Fig. 2. Animated aurora ovals as a function of K_p index [0…8] and time for 24th December 2009

Figure: The statistical auroral oval (green) as a function of Kp index and for varying UT time (Sigernes, 2010). Polar cap is located inside the oval.

Characteristics of D region

- Small electron densities, large neutral densities
- Complex chemistry including ion production and recombination processes, also transport, that are not fully understood

SIC model positive ions

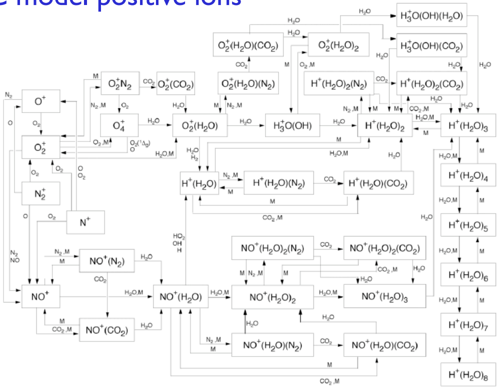


Figure: Sodankylä Ion Chemistry model (SIC), positive ions.

Characteristics of D region

- Small electron densities, large neutral densities
- Complex chemistry including ion production and recombination processes, also transport, that are not fully understood

SIC model
negative ions

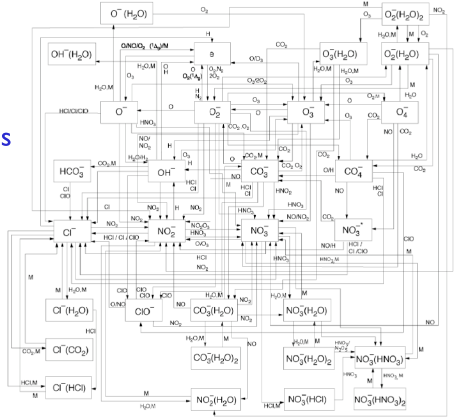


Figure: Sodankylä Ion Chemistry model (SIC), negative ions.

Characteristics of E region

- Due to different collision and gyro frequencies for ions and electrons, electrical conductivities maximize in the E region and may be greatly enhanced due to auroral particle precipitation.
- Horizontal currents flow in the E region.

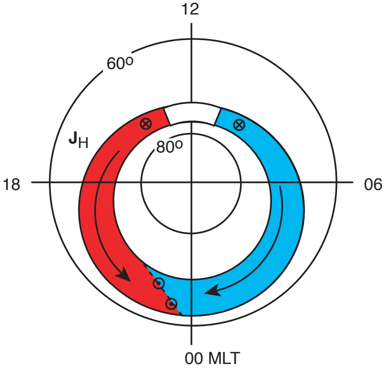


Figure: Hall currents within the auroral oval: eastward electrojet (red) and westward electrojet (blue).

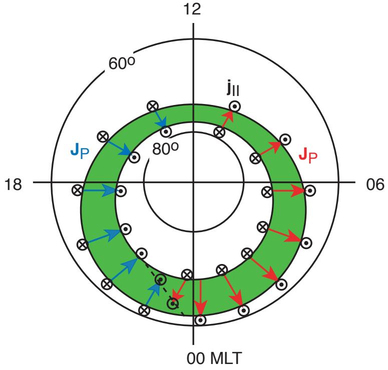


Figure: Pedersen and field-aligned currents within the auroral oval.

Characteristics of F region

- Maximum electron densities occur at F-region maximum (h $\sim$ 300 km).
- Collisions with neutrals become sparse both for ions and electrons, hence both species drift with the same convection velocity of $\mathbf{v} = \mathbf{E}x\mathbf{B}/B^2$.
- Ambipolar diffusion becomes important.
- At high latitudes, ion outflows may take place and field-aligned currents flow.

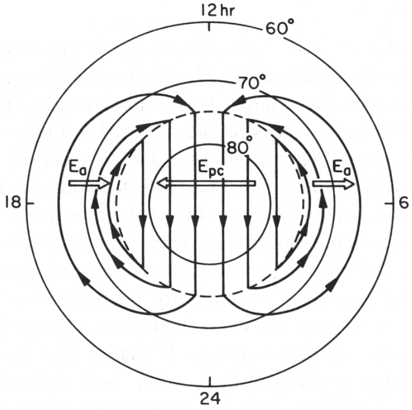
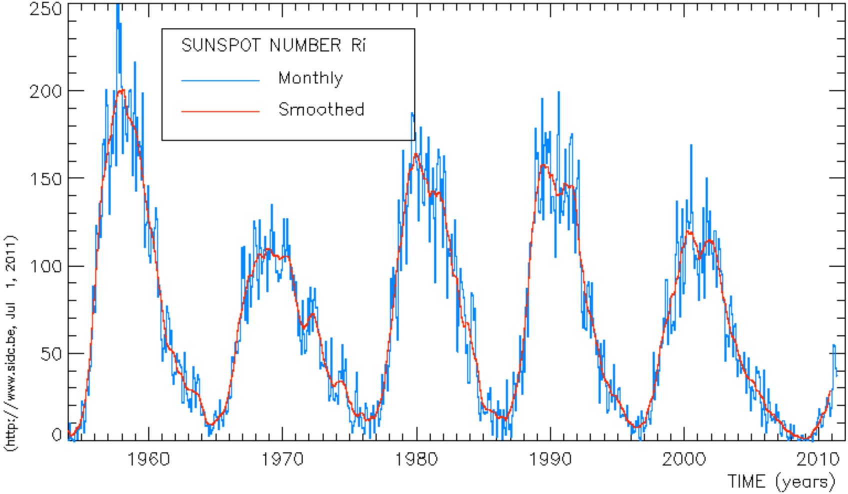


Figure: Plasma convection in the northern high latitude ionosphere and associated convection electric fields.

Current solar activity

- Activity is slowly rising after the deep solar minimum.
- Task: Check the current solar wind conditions and predictions from: http://www.spaceweather.com/ !



Literature

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